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MTF Test of Proposed Low-Beta Cooling Procedure

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At the request of George Mulholland a comparison was made of results using two cooling procedures for a dipole magnet. Although the final application involves quadrupole magnets, a dipole was selected for the test because it provides a better approximation to the length of the magnet string involved. Figure 1 shows the portion of valving used in cooling a magnet at MTF.

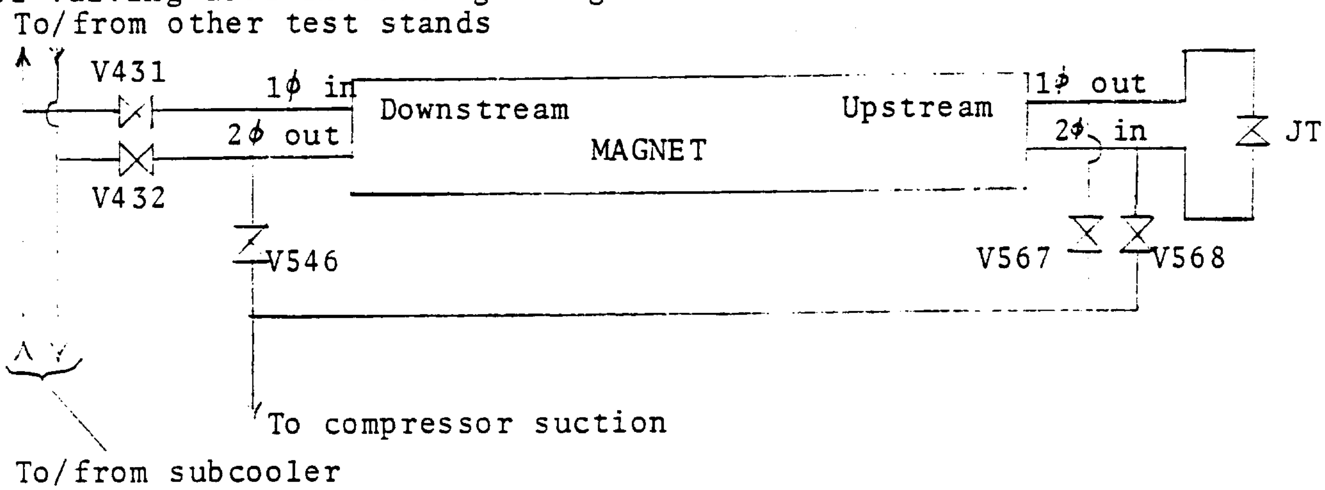


Figure 1

During a standard cooldown V567, V568, and the JT valve are open; other valves are closed. Then V431 is opened to begin the cooldown. When the 1ϕ out flow reaches LHe temperature, V546 is opened to complete the cooling of the 2ϕ passages of the magnet and V567 and V568 are closed. When all 4 flows (1ϕ in, 1ϕ out, 2ϕ in, 2ϕ out) are at LHe temperature V431 is closed and V432 is opened to cool the transfer line between V432 and the magnet. Then V431 is re-opened and V546 is closed. At this point only V431, V432, and the JT valve are open; the JT is set to establish proper pressure, flow, and temperature distributions. The total time for this cooldown procedure is typically 4½ hours.

The proposed low-beta cooldown procedure begins with only the JT valve and V546 open. Then V431 is opened to begin the cooldown. When all 4 flows (1ϕ in, 1ϕ out, 2ϕ in, 2ϕ out)are at LHe temperature V431 is closed and V432 is opened to cool the transfer line. Then V432 is closed until it is barely cracked, V546 is closed, and V431 is opened to establish a normal flow path. At this point only V431, V432, and the JT valve are open. The JT valve is left wide open and V432 is used to control the flow through the magnet. The total time for this cooldown procedure on magnet TB0381 (test stand 5) was 12¼ hours.

The extra step of cooling the 2ϕ transfer line is needed at MTF to avoid the disruption of cooling to other magnets being tested. This step should not be needed for the low-beta cooldown; however, it takes less than 10 minutes and does not significantly affect our cooldown times.

With the standard cooldown procedure, warm gas from the magnet returns to suction without passing back through the magnet. With the modified cooldown procedure, warm gas from the magnet 1φ passes back through the magnet 2φ and heat exchanges with the magnet 1φ heating the "1φ" liquid/gas. This results in the longer cooldown time using the modified cooldown procedure. The mean indicated 1φ in transfer line flow (from a venturi gauge in the transfer line) was between 6 and 7 gram/sec helium for both cooldown procedures. The cooldown parameters for the two procedures are summarized in Table 1 below.

Table 1

	Standard cooldown	Low-beta cooldown
1φ LHe input flow	6-7 g/sec	6-7 g/sec
1φ LHe input pressure	10 psig	10 psig
1φ LHe input temperature	4.65 K	4.65 K
LN2 shield input flow	300 SCFH	300 SCFH
Warm bore in place	Yes	Yes
LN2 in warm bore	No	Yes
Time for cooldown	4½ hours	12¼ hours

It should be noted that the inside of the warm bore is normally filled with LN2 during quench testing to more nearly duplicate tunnel conditions (under which the magnet bore is at LHe temperature). The warm bore consists of a double walled "tube" with superinsulation and vacuum between the two walls. This permits measurement instrumentation to be inserted into the magnet bore with the bore at LHe temperature. The outer wall of the warm bore is in thermal communication with the magnet bore tube. The inner wall of the warm bore is either at approximately room temperature or at LN2 temperature depending upon whether the warm bore is open or has LN2 in it. The effect of the warm bore on quench performance is small. With 10(-4) torr warm bore vacuum, quench currents with and without LN2 in the warm bore differ by less than 50 amp. With poor warm bore vacuum, quench currents differ by as much as 300 amp. Normal warm bore vacuum is better than 10(-5) torr. The warm bore has negligible effect on cooldown times.

A comparison of quench performance was made using the MTF program "Cycle" for the two types of cooling. Cycle ramps the magnet at a ramp rate of about 200 amp/sec to a target flattop current, holds the flattop current for 20 seconds, and then ramps the magnet back down at the same rate. The minimum current between ramps is 400 amps. A requirement for the test to be considered valid is that 8 ramps be completed at the initial target current without a quench. After the 8 ramps have been completed, the target current is incremented by 50 amps. The program continues incrementing by 50 amps. every second ramp until a quench occurs. For standard cooling, Cycle was run under only one set of cooling conditions. For low-beta type cooling, Cycle was run with three different LHe flow rates. The results are summarized in Tables 2a and 2b.

Table 2a. Cycle test with standard cooling

Cooling parameters:

	1ϕ in	1ϕ out	2ϕ in	2ϕ out
Press. (psig):	9.20	9.20	4.30	4.10
VPT (psig):	5.80	7.10	4.00	4.00
Subcooling (psi):	3.40	2.10	0.30	0.10
Temperature (K):	4.59	4.66	4.48	4.48
1ϕ flow (g/sec):	23.1			
Lead flow (SCFH air):	95			
LN2 shield flow (SCFH):	300			
LN2 in warm bore:	Yes			

Cycle results:

Target current (amp):	4335	4386	4436
Ramp rate (amp/sec):	201	201	201
Ramps completed:	8	2	0
Current at which quench occurred (amp):	---	---	4436
Time flattop reached after start of ramp (sec):	---	---	20.2
Time quench occurred after start of ramp (sec):	---	---	25.3

Table 2b. Cycle test with low-beta type cooling

Set 1: 20 g/sec flow

Cooling parameters:

	1ϕ in	1ϕ out	2ϕ in	2ϕ out
Press. (psig):	9.10	9.50	9.50	9.10
VPT (psig):	6.70	9.00	9.00	9.40
Subcooling (psi):	2.40	0.50	0.50	-0.30
Temperature (K):	4.64	4.76	4.76	4.78
1ϕ flow (g/sec):	19.7			
Lead flow (SCFH air):	95			
LN2 shield flow (SCFH):	300			
LN2 in warm bore:	Yes			

Cycle results:

Target current (amp):	4136	4156	4175
Ramp rate (amp/sec):	201	201	202
Ramps completed:	8	2	0
Current at which quench occurred (amp):	---	---	4176
Time flattop reached after start of ramp (sec):	---	---	18.9
Time quench occurred after start of ramp (sec):	---	---	19.8

Table 2b. (Continued)

Set 2: 25 g/sec flow

Cooling parameters:

	1ϕ in	1ϕ out	2ϕ in	2ϕ out
Press. (psig):	8.90	9.30	9.20	8.80
VPT (psig):	5.90	8.60	8.60	9.00
Subcooling (psi):	3.00	0.70	0.60	-0.20
Temperature (K):	4.59	4.74	4.74	4.76

1ϕ flow (g/sec):	25.1
Lead flow (SCFH air):	90
LN2 shield flow (SCFH):	300
LN2 in warm bore:	Yes

Cycle results:

Target current (amp):	4136	4156	4176	4196	4217
Ramp rate (amp/sec):	201	201	201	202	202
Ramps completed:	8	2	2	2	2
Current at which quench occurred (amp):	---	---	---	---	---
Time flattop reached after start of ramp (sec):	---	---	---	---	---
Time quench occurred after start of ramp (sec):	---	---	---	---	---

Target current (amp):	4237
Ramp rate (amp/sec):	202
Ramps completed:	0
Current at which quench occurred (amp):	4237
Time flattop reached after start of ramp (sec):	19.2
Time quench occurred after start of ramp (sec):	29.3

Table 2b. (Continued)

Set 3: 29 g/sec flow

Cooling parameters:

	1ϕ in	1ϕ out	2ϕ in	2ϕ out
Press. (psig):	9.80	10.20	10.00	9.80
VPT (psig):	6.70	8.90	9.00	9.10
Subcooling (psi):	3.10	1.30	1.00	0.70
Temperature (K):	4.64	4.76	4.76	4.77
1ϕ flow (g/sec):	29.0			
Lead flow (SCFH air):	95			
LN2 shield flow (SCFH):	300			
LN2 in warm bore:	Yes			

Cycle results:

Target current (amp):	4134	4155	4175	4194	4216
Ramp rate (amp/sec):	201	201	202	201	201
Ramps completed:	8	2	2	2	2
Current at which quench occurred (amp):	---	---	---	---	---
Time flattop reached after start of ramp (sec):	---	---	---	---	---
Time quench occurred after start of ramp (sec):	---	---	---	---	---

Target current (amp):	4236	4256
Ramp rate (amp/sec):	201	202
Ramps completed:	2	0
Current at which quench occurred (amp):	---	4255
Time flattop reached after start of ramp (sec):	---	19.3
Time quench occurred after start of ramp (sec):	---	28.5

Table 2. (Continued)

Notes:

1) Pressure gauges are accurate to about 0.25 psi.
2) VPT pressure gauges are accurate to about 0.15 psi.
3) Lead flow is in SCFH air equivalent for each of 2 leads. To obtain flow in liter/hour of LHe multiply by 0.109.
4) The calibration used for venturi flowmeters is that a differential pressure Delta P (inches water) is related to flow F (gram/sec LHe) by:

$$F = 7.5\ (\text{Delta P})^{\frac{1}{2}}.$$

5) The ramp rate reported is the average between 10% and 90% points of the ramp.
6) The current between ramps is typically 410 amp.
7) Tests with standard cooling used the standard icrement of 50 amp. between currents.
8) For tests with low-beta type cooling, the increment was reduced to 20 amp. for better resolution of quench current.

The dependence of Cycle quench current on 1ϕ flow, 1ϕ out sub-cooling, and the product of flow and sub-cooling is shown in Figures 2a, 2b, and 2c. It should be noted that for a given cryogenic *installation, flow and sub-cooling are coupled, in general.* These plots are made from Table 2b. Since input and output 1ϕ temperatures are comparable for each of the three flow rates, quench currents should require minimal correction for temperatures and no corrections have been made in plotting the figures.

Aside from temperature, the dominant cooling parameter affecting Cycle current is the 1ϕ flow rate. This can be seen by comparing Cycle results with low-beta type cooling with the Cycle result with standard cooling. The flow rate with standard cooling was 23.1 g/sec. For this flow rate, Figure 2a predicts a Cycle current of about 4213 amp.

For Fermilab superconductor cable, the dependence of quench current on temperature is approximately given by:

$$\frac{\Delta I}{I} = -2.3 \frac{\Delta T}{T}.$$

For low-beta cooling, I = 4213, T = 4.75K. For standard cooling, T = 4.66K. Then:

$$I = -2.3 \left(\frac{-.09}{4.75}\right) (4213) = 184 \text{ amp.}$$

So *the predicted standard cooling quench current would be*

$$4213 + 184 = 4397 \text{ amp.}$$

The measured quench current was 4436 amp. which agrees well with the prediction given the 50 amp. granularity of the Cycle test with standard cooling and the 20 amp. granularity with low-beta type cooling.

This result is consistent with the MTF view that provided sub-cooling exceeds some threshold (canonically taken to be about 0.5 psi at MTF), quench results are, to first order, independent of sub-cooling.

Figure 2a. Cycle quench current versus flow with low-beta type cooling

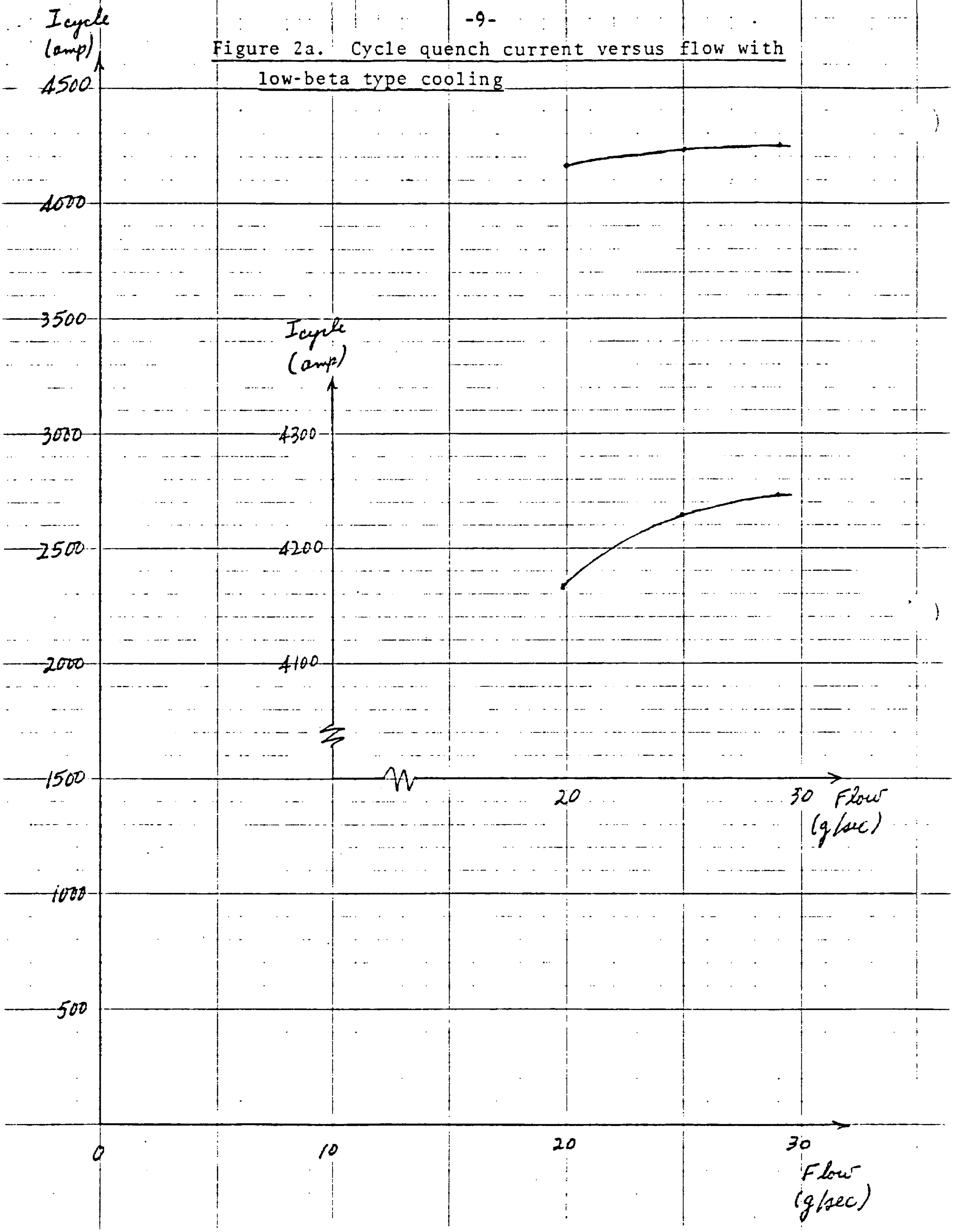


Figure 2b. Cycle quench current versus sub-cooling with low-beta type cooling

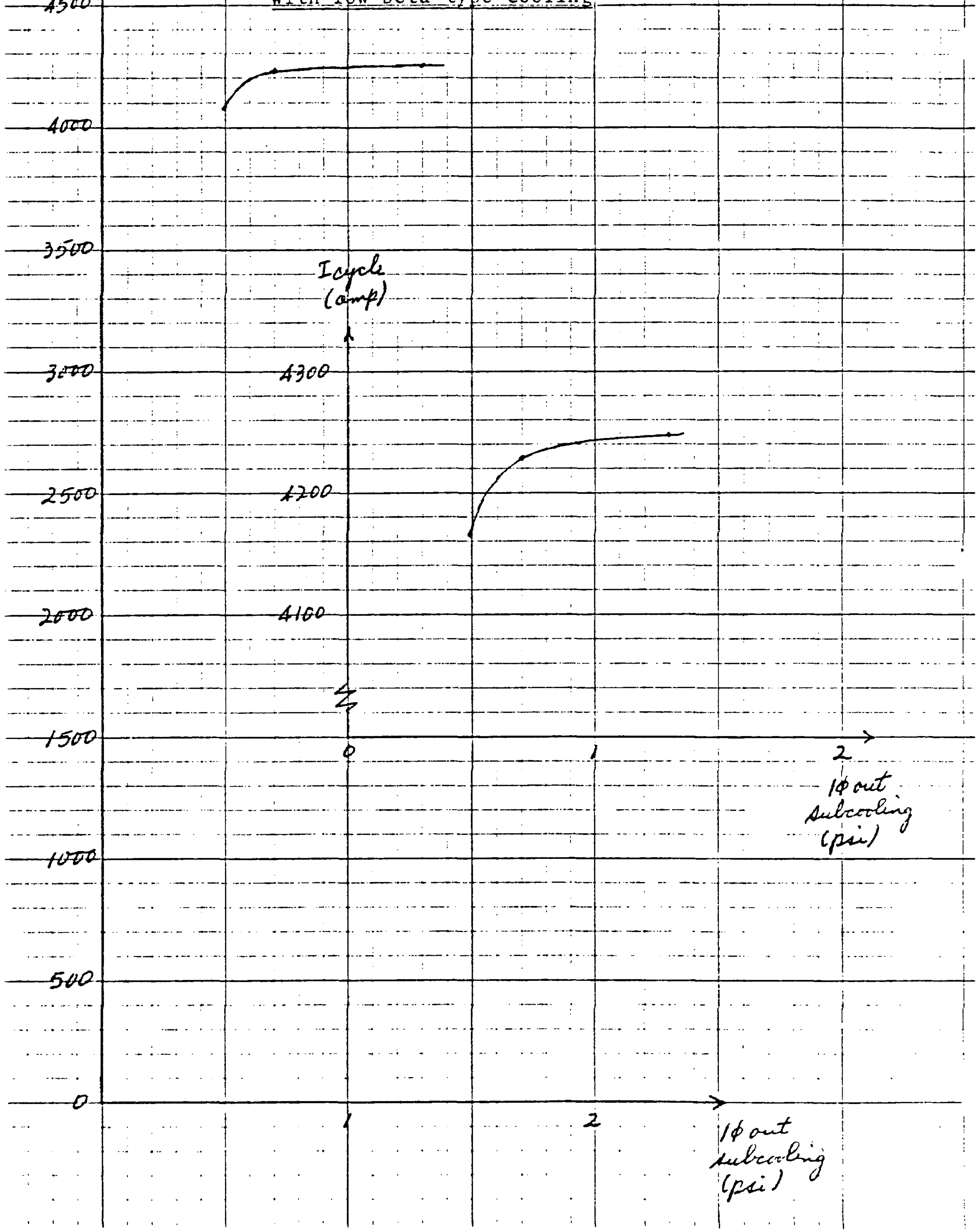
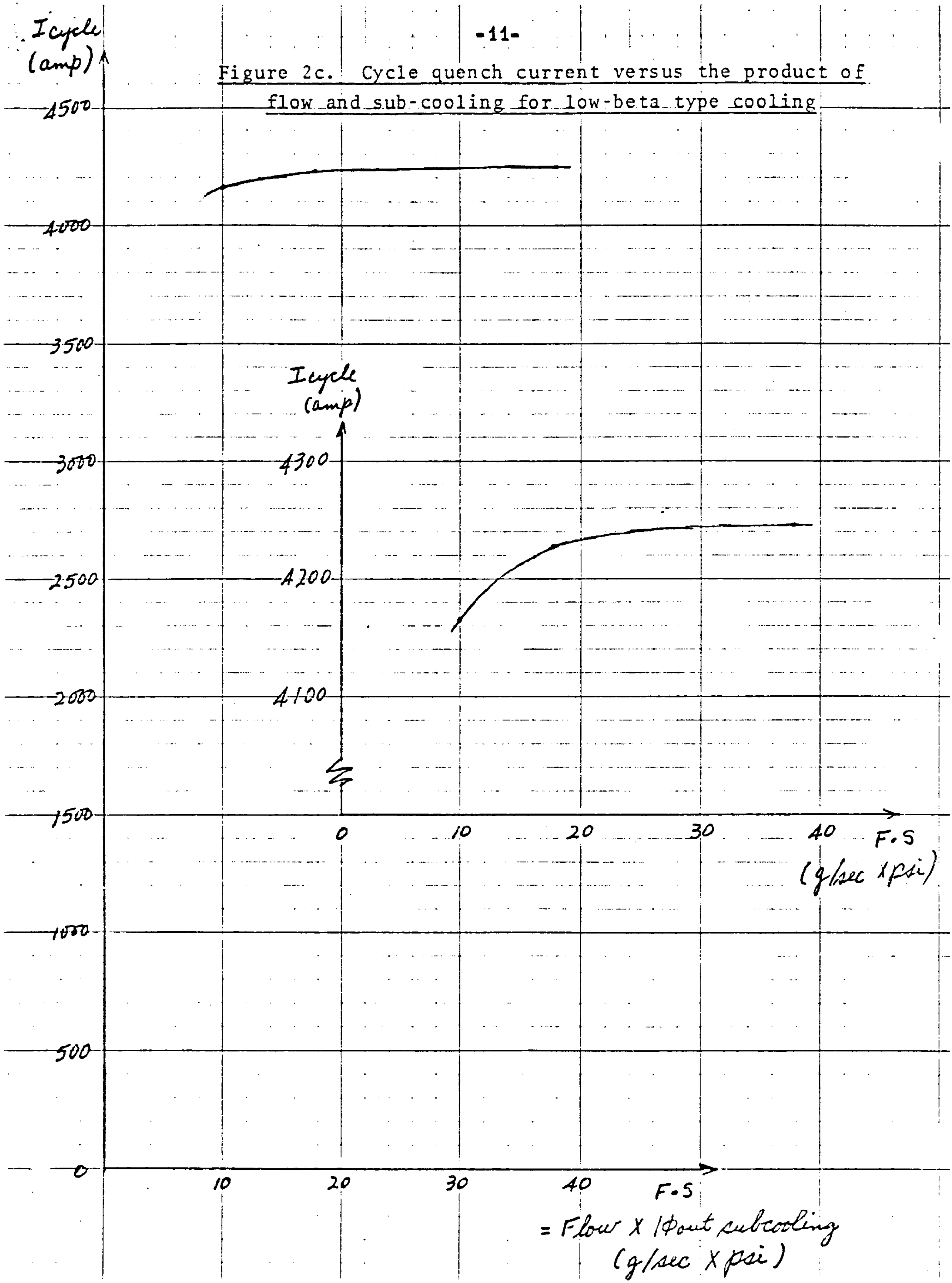


Figure 2c. Cycle quench current versus the product of flow and sub-cooling for low-beta type cooling



Three sets of measurements were taken in an effort to see the effect of ramp rate on cooling conditions for low-beta type cooling. The first set of cooling conditions was recorded with zero magnet current. The remaining two sets were recorded while ramping to a nominal flattop current of 4000 amp. with a 20 second flattop, a nominal 400 amp. minimum current, and two seconds between ramps. For each set of conditions, we waited until an equilibrium cooling appeared to be reached. The results are shown in Table 3.

The ramping heat load can be predicted from MTF AC Loss data. Figure 3 shows AC Loss per ramp cycle as a function of flattop current and ramp rate. The data in the figure are raw: no corrections have been applied. Figure 3a shows that loss is approximately linear with flattop current. Figure 3b shows that loss is approximately independent of ramp rate. From Figure 3a, loss/ramp cycle is about 520 joules for a flattop current of 4000 amp. The loss for a ramp from 400 amp. to 4000 amp. should be 0.9 (520) joules = 468 joules. For a 200 amp/sec ramp rate, a 20 second flattop, and 2 seconds between ramps, a ramp cycle should take 58 seconds. Then the AC Loss heat load should be 468/58 = 8.1 watts. For a 100 amp/sec ramp rate, the corresponding number is 5.0 watts. Figure 4 shows the predicted AC Loss heat load as a function of ramp rate for ramps of the type used in the measurements. It is believed that MTF AC Loss data may be systematically high by as much as 15%.

The data in Table 3 are inconsistent with this picture if one assumes 100% liquid in the 1ϕ and 2ϕ; the 1ϕ heat load would be too high and the 2ϕ heat load too low. I conclude that the 2ϕ was not filled with 100% liquid and that the 1ϕ probably was not either. I have requested that the measurement be repeated. If it were repeated the following changes should be made:

1) The measurement should be done on test stand 1. I believe that this stand has substantially better cooling properties than other stands.
2) The flattop time should be reduced to near zero to maximize the effect of the AC Loss heat load.
3) The time between ramps should be reduced to near zero for the same reason.
4) Cooling of other stands should be suspended to maximize the liquid content of 1ϕ delivered to test stand 1.
5) Each VPT and pressure gauge should be calibrated immediately before the measurement. If possible, higher quality gauges should be installed.
6) The measurements should be made over a greater range of ramp rates.

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Table 3. Ramp rate dependence of temperatures for low-beta type cooling

	1ϕ in	1ϕ out	2ϕ in	2ϕ out
Set 1: Zero current				
Pressure (psig):	9.50	9.65	9.55	9.55
VPT (psig):	6.30	9.05	9.35	9.45
Subcooling (psi):	3.20	0.60	0.20	0.10
Temperature (K):	4.62	4.76	4.78	4.79
1ϕ flow (g/sec): 20.1				
Set 2: 100 amp/sec ramp rate				
Pressure (psig):	9.50	9.75	9.60	9.60
VPT (psig):	6.50	9.30	9.40	9.45
Subcooling (psi):	3.00	0.45	0.20	0.15
Temperature (K):	4.63	4.78	4.78	4.79
1ϕ flow (g/sec): 19.5				
Set 3: 200 amp/sec ramp rate				
Pressure (psig):	9.40	9.80	9.50	9.55
VPT (psig):	6.35	9.30	9.45	9.50
Subcooling (psi):	3.05	0.50	0.05	0.05
Temperature (K):	4.62	4.78	4.79	4.79
1ϕ flow (g/sec): 19.9				

Notes:

1) Lead flow = 95 SCFH air equivalent.
2) LN2 shield flow = 300 SCFH.
3) LN2 present in warm bore.
4) Accuracy of pressure gauges is about 0.25 psi.
5) Accuracy of VPT pressure gauges is about 0.15 psi.

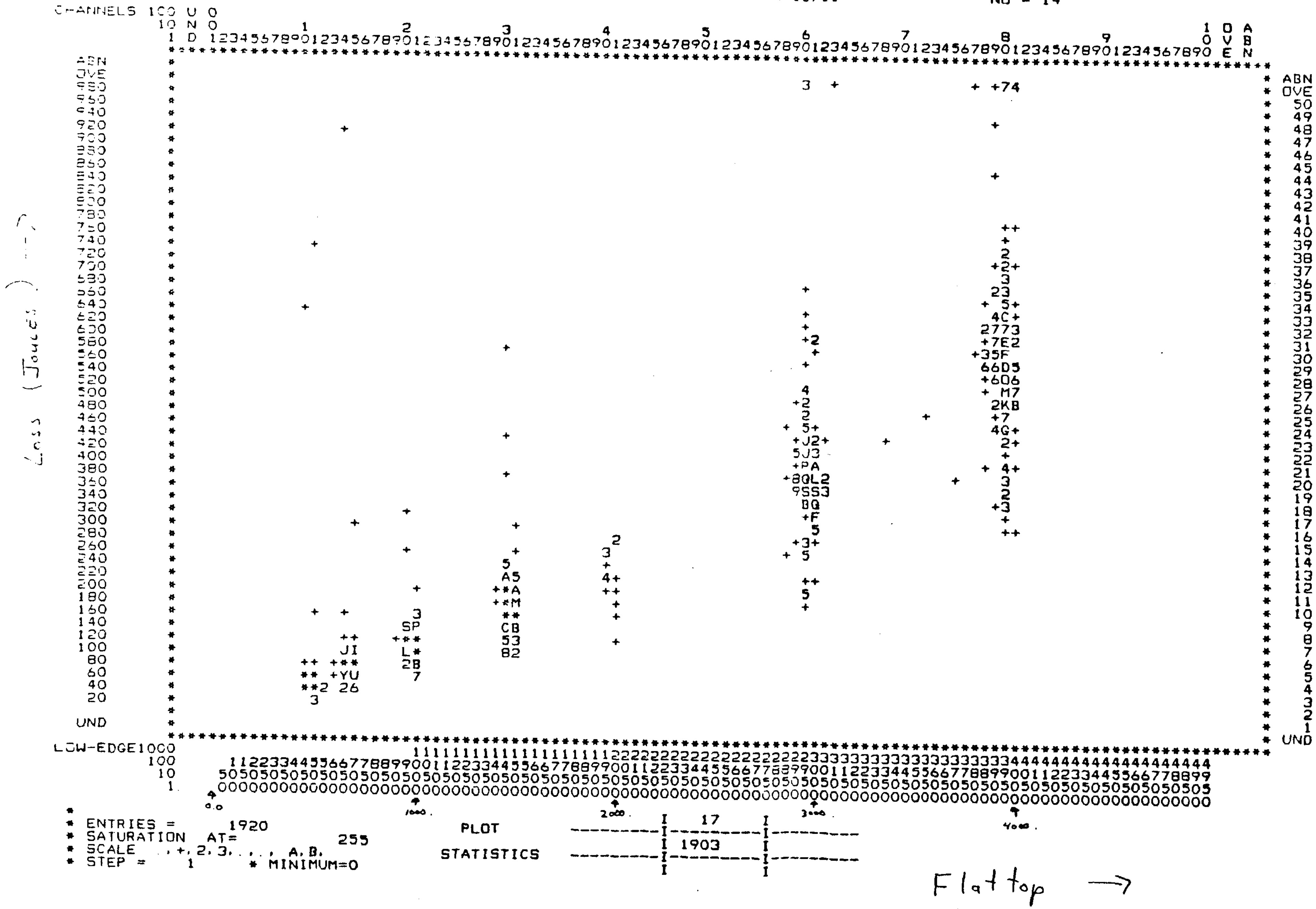
ADDED DATA FOR DIPOLES, ALL STANDS

FLATTOP VERSUS LOSS

HBOOK ID = 40

Figure 3a. AC Loss per ramp cycle versus flattop current *

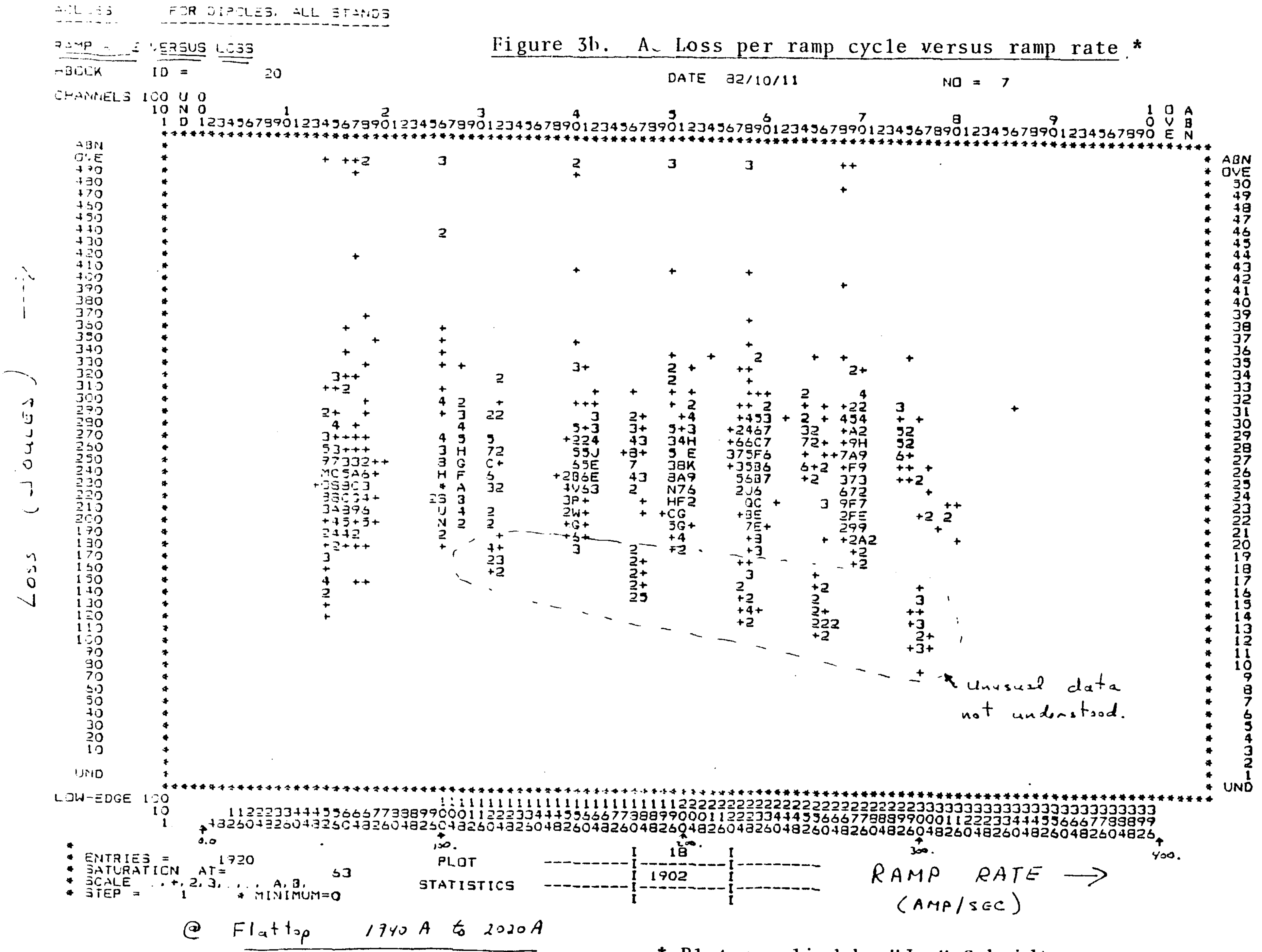
DATE 82/10/11 NO = 14



@ Ramp Rate 180 A/sec to 240 A/sec

* Plot supplied by "Jay" Schmidt.

Figure 3b. A. Loss per ramp cycle versus ramp rate.*



* Plot supplied by "Jay" Schmidt.

Figure 4. AC Loss heat load as a function of ramp rate

Minimum current = 400 amp.
Flattop current = 4000 amp.
Flattop time = 20 seconds.
Time between ramps = 2 seconds.